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Research article

Harnessing landscape heterogeneity for managing future disturbance risks in forest ecosystems

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ABSTRACT

In order to prevent irreversible impacts of climate change on the biosphere it is imperative to phase out the use of fossil fuels. Consequently, the provisioning of renewable resources such as timber and biomass from forests is an ecosystem service of increasing importance. However, risk factors such as changing disturbance regimes are challenging the continuous provisioning of ecosystem services, and are thus a key concern in forest management. We here used simulation modeling to study different risk management strategies in the context of timber production under changing climate and disturbance regimes, focusing on a 8127 ha forest landscape in the Northern Front Range of the Alps in Austria. We show that under a continuation of historical management, disturbances from wind and bark beetles increase by +39.5% on average over 200 years in response to future climate change. Promoting mixed forests and climate-adapted tree species as well as increasing management intensity effectively reduced future disturbance risk. Analyzing the spatial patterns of disturbance on the landscape, we found a highly uneven distribution of risk among stands (Gini coefficients up to 0.466), but also a spatially variable effectiveness of silvicultural risk reduction measures. This spatial variability in the contribution to and control of risk can be used to inform disturbance management: Stands which have a high leverage on overall risk and for which risks can effectively be reduced (24.4% of the stands in our simulations) should be a priority for risk mitigation measures. In contrast, management should embrace natural disturbances for their beneficial effects on biodiversity in areas which neither contribute strongly to landscape-scale risk nor respond positively to risk mitigation measures (16.9% of stands). We here illustrate how spatial heterogeneity in forest landscapes can be harnessed to address both positive and negative effects of changing natural disturbance regimes in ecosystem management.

1. Introduction

The decoupling of human development from the use of fossil resources in order to halt climate change is a major challenge of the 21st century. In response to this challenge political programs increasingly foster a bio-based and circular economy, aiming to reduce overall resource use, and substitute fossil resources with sustainably sourced renewable materials (Pülzl et al., 2014; Staffas et al., 2013). Forest ecosystems cover more than 30% of the global land area and are a primary source of renewable resources for humans. Consequently, the demand for timber and fiber from forests is increasing (FAO, 2017). Outlook studies for the forest sector project a further increase in the demand for biomass from forests for the near- to mid-term future (UNECE and FAO, 2011). At the same time the land base for sustainable forest management is decreasing (Hansen et al., 2013), due to the land-use changes resulting from a growing human population. Furthermore, the efforts to combat biodiversity loss, another crucial planetary challenge of the 21st century (Steffen et al., 2015), require an increasing amount of land to be set aside for conservation purposes (Belote et al., 2017). This land is henceforth no longer available for the provisioning of renewable resources to society. Finally, there is an increasing recognition that the wellbeing of a growing human population depends on a variety of ecosystem services beyond the provisioning of timber and fiber, including regulating, cultural, and supporting services (MA, 2005). Managing ecosystems for a wide

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range of different ecosystem services can reduce the provisioning of individual services such as biomass production, as trade-offs between ecosystem services are common (Lafond et al., 2017; Langner et al., 2017). Consequently, while the demand for biomass from forests is growing, ongoing societal changes make its provisioning increasingly complex.

In addition to societal changes also environmental stressors complicate the sustainable provisioning of biomass from forests, and thus pose risks for an emerging bioeconomy. Factors such as anthropogenic climate change or the human alterations of the global nitrogen cycle have profound impacts on the natural dynamics of ecosystems (Steffen et al., 2015). In past decades, biomass production has largely benefitted from environmental changes in areas such as Central Europe, with longer growing seasons, CO_2 fertilization, and N deposition accelerating forest growth (Pretzsch et al., 2014). While these positive effects are expected to continue in the short term, increases in natural disturbances such as extended drought periods, wildfires, insect outbreaks, and windstorms could compensate or even reverse such positive effects of global change (Nabuurs et al., 2013; Reyer et al., 2017). The impact of natural disturbances has already increased in forests around the globe, and is expected to further intensify in the coming decades in response to ongoing changes in the climate system (Seidl et al., 2017a). Both scientists and forestry professionals expect alterations in the disturbance regime to be among the most profound impacts climate change will have on forest ecosystems (Lindner et al., 2010; Seidl et al., 2016a).

Natural disturbances abruptly and lastingly alter forest structures, and have largely negative impacts on the sustainable and continuous provisioning of ecosystem services (Thom and Seidl, 2016). Consequently, forest risk management has long sought to prevent the occurrence of natural disturbances, or to reduce their impacts (Hanewinkel et al., 2011). However, traditional approaches of risk management have been of only limited success, as evidenced by a steady increase in the timber damaged by natural disturbances over past decades, e.g. in Europe (Seidl et al., 2014b). Furthermore, natural disturbances fulfill a number of important functions in forest ecosystems, such as contributing to their adaptive capacity (Thom et al., 2017b) and fostering biodiversity (Beudert et al., 2015; Wermelinger et al., 2017). Consequently, natural disturbances are increasingly seen as an integral part of ecosystem management (Kulakowski et al., 2017). For operational forest planning this poses the question of how to integrate natural processes such as disturbances into management while meeting an increasing level of biomass demand. The complexity of addressing disturbances in management is further increased by the fact that natural disturbance regimes are changing rapidly, possibly transgressing their natural range of variability in coming decades (Kulakowski et al., 2017; Seidl et al., 2017a). Consequently, an improved management of disturbance risks is needed in forestry, incorporating natural disturbances processes into management while at the same time safeguarding a continuous biomass provisioning for society.

As a result of the long history of considering disturbance risks in forest management a wide variety of risk management tools exist today. Predisposition assessment systems have, for instance, been used to identify areas at particular risk within a landscape, based on site classification and stand attributes (Hanewinkel et al., 2011; Netherer and Nopp-Mayr, 2005). Such systems are widely used in operational forest management today. They, however, assume forest ecosystems to be static, and are not able to address changing environmental conditions and their effects on disturbance risk. A second set of tools widely used for forest risk management are simulation models (Hanewinkel et al., 2011; Seidl et al., 2011). These approaches address disturbance risks more dynamically, e.g., quantifying the possible impact of wind disturbances on timber resources (Albrecht et al., 2015; Blennow et al., 2010). Yet, most approaches to date have focused on the stand scale (but see e.g., Cairns et al., 2008; Zeng et al., 2010), making landscape dynamics and heterogeneity important frontiers of forest risk research (Turner et al., 2013).

Here, we propose that the spatial heterogeneity within a managed forest landscape can be utilized to stratify risk management approaches, and unify the different management perspectives on natural disturbances (prevent vs. embrace). Specifically, we investigate (i) the spatial variation in the contribution of individual stands to landscape-scale risks and goals in the context of timber production, as well as (ii) the spatially variable response of stands to risk management strategies. Our analysis specifically addresses the question of how priority areas for different management responses to disturbance (e.g., actively reduce disturbance risk in management vs. let natural disturbance processes develop unimpeded) can be identified on the landscape. We hypothesized that (1) disturbance risk will increase substantially with climate change, but (2) that the contribution of individual stands to the overall risk at the landscape scale (and thus their leverage in risk management) is not uniform. Furthermore, we expected that not only risk varies spatially on the landscape, but that (3) also the response of individual stands to risk mitigation measures is not uniform (i.e., different levels of risk control exist on the landscape).

2. Methods and materials

2.1. Study landscape

Questions of spatial variation in disturbance and risk management were addressed for the Weissenbachtal landscape, located in the Northern Front Range of the Alps in Austria (N 47.78°, E 13.59°). The geology of the region is dominated by calcareous bedrock consisting mainly of limestone and dolomite. Common soil types are Chromic Cambisols and Rendzic Leptosols with Moder and Tangel humus types (Mayer et al., 2017). The Weissenbachtal landscape extends over 8127 ha, of which 5716 ha are stockable forest area. It is representative for managed forests in Central Europe in several ways: First, it is characterized by considerable environmental heterogeneity, extending over an elevational gradient from 490 m to 1400 m. Mean annual temperature is 7.5 °C, with temperatures decreasing sharply with elevation (from 9.6 °C to 5.5 °C). Precipitation is ample and increases with elevation (1,207 mm to 2,071 mm, with a landscape mean of 1,503 mm), with 57.5% of the precipitation occurring between April and September. Second, the natural vegetation of the landscape is dominated by Norway spruce (*Picea abies* (L.) Karst.), silver fir (*Abies alba* Mill.), and European beech (*Fagus sylvatica* L.), which are the three most important late-seral tree species in Central Europe above ca. 500 m in elevation. Specifically, the natural vegetation <800 m asl. is dominated by beech at Weissenbachtal. In mid elevations spruce and fir increase in competitiveness, with areas >800 m asl. being characterized by a mixed forest type of spruce, fir and beech (Kilian et al., 1994). Third, the landscape has a long and intensive management history, and was primarily used to provide fuel wood for the production of salt from a nearby mine. Densities of wild ungulates were historically high, due to the area being a favored hunting ground of the Austrian imperial family throughout the 19th and early 20th century. Reflecting this management history, the current vegetation structure and composition differs substantially from natural conditions. Spruce was historically favored for timber production, and 48.9% of the growing stock on the landscape are currently spruce. Fir, on the other hand, suffered considerably from clear-cut management and high game densities, and currently only makes up 2.2% of the growing stock on the landscape. Stand

structures strongly reflect past management and disturbance, with younger stands in low-elevation areas and wind-prone ridges, and older stands predominately in higher elevations (Fig. 1). The landscape is currently under the stewardship of the Austrian Federal Forests (AFF).

2.2. Simulation model

To project the potential future risk from natural disturbances and assess the effectiveness of risk management alternatives we used the simulation model iLand, the individual-based forest landscape and disturbance model. iLand is a process-based forest landscape model, simulating forest vegetation dynamics at the grain of individual trees (Seidl et al., 2012a). Competition for resources is modeled via an approach rooted in ecological field theory, and resource utilization follows a light use efficiency approach (Landsberg and Waring, 1997). Environmental constraints for production are considered on a daily time step. Allocation of the assimilated carbohydrates is modeled based on tree size and allometric ratios. In the simulation, trees are adaptive agents which dynamically respond to their environment, e.g., by allocating more resources to root growth if limited by water and/or nutrients, or by favoring height growth over diameter growth if experiencing strong competition for light from neighbors (Seidl et al., 2012a). Seeds are dispersed from mature trees in a spatially explicit manner. Germination and establishment of seedlings are determined by environmental filters and light availability, the latter calculated dynamically at a 2 × 2 m horizontal resolution, based on the presence and distribution of overstorey trees (Seidl et al., 2012b). Mortality considers both age-related mortality and stress-related mortality, with stress being defined as a tree experiencing carbon starvation.

In addition to factors of individual-tree mortality iLand also simulates mortality from natural disturbances. For the current analysis, we employed process-based submodules for disturbances by wind and bark beetles, specifically the European spruce bark beetle (*Ips typographus* L.), which are currently the most important abiotic and biotic disturbance agents in the region (Thom et al., 2013; Tomiczek et al., 2012). Wind disturbances are modeled based on dose-response relationships at the level of individual trees, accounting for both upwind gap size and local sheltering from neighboring trees, and dynamically tracking changes in forest structure during a wind event (Seidl et al., 2014a). Downed Norway spruce trees provide optimal breeding conditions for the European spruce bark beetle. Temperature-dependent population development of beetles is modeled using a phenological approach, with dispersal and host search being computed spatially explicitly (Seidl and Rammer, 2017). The simulated natural disturbance dynamics is thus an emergent property of the interplay between climate, forest structure and composition, as well as dynamically interacting disturbance agents.

In addition to natural processes iLand includes a detailed, agent-based model of forest management (ABE, Rammer and Seidl, 2015). ABE simulates management agents that dynamically adapt their interventions to changes in the environment. To simulate different management alternatives, the user provides the model with stand treatment programs, i.e., generalized sequences of silvicultural interventions over the course of stand development. In the simulation, the management agent dynamically applies these programs, and adapts them where necessary, accounting for both stand- and

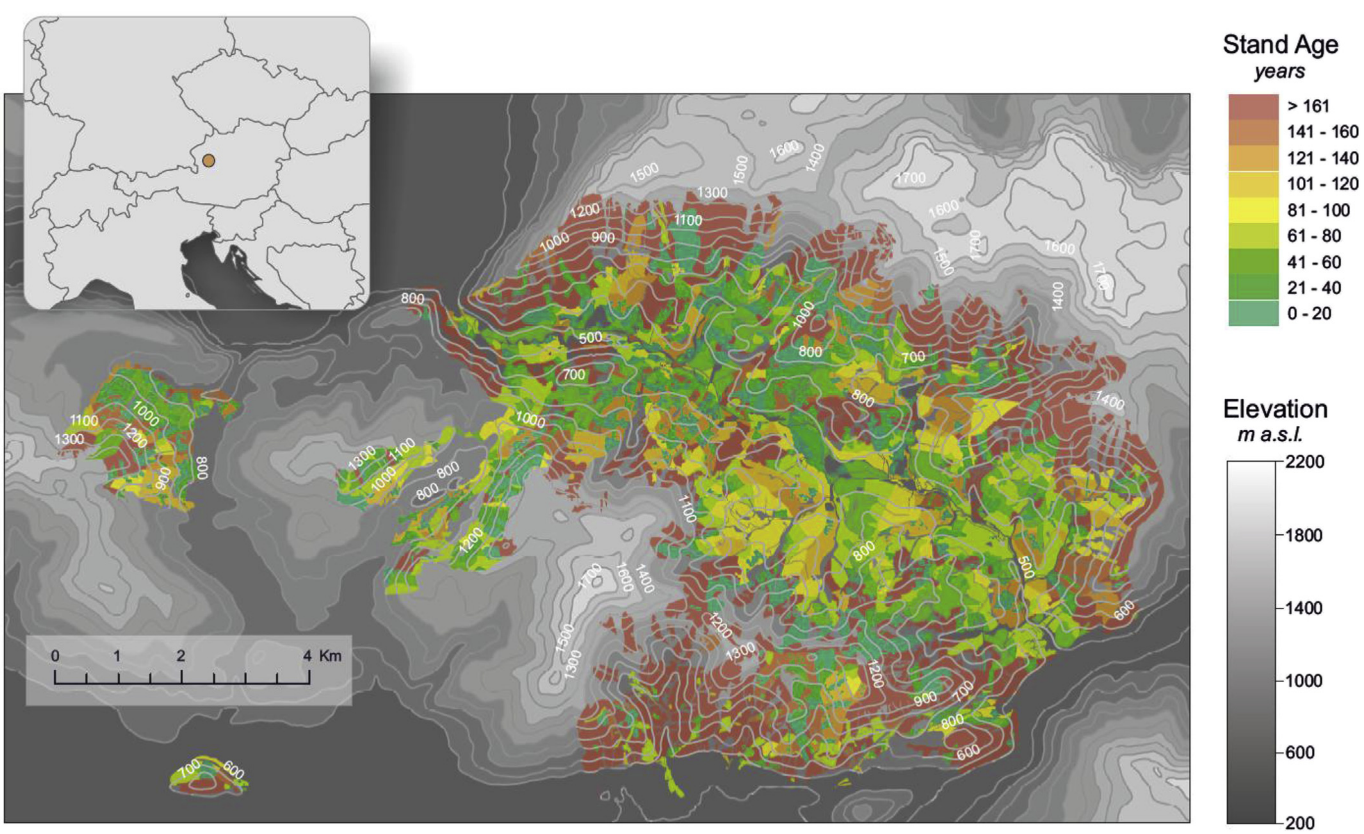

Fig. 1. The Weissenbachtal landscape (main panel), situated in the Northern Front Range of the Alps in Austria (insert). Isolines and shades of grey show elevation above sea level. Polygons delineate the 1678 stands forming the base entities of management, with colors indicating current stand age. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

landscape-level constraints. At the stand level, the management agent is, for instance, able to observe adjacency rules, i.e. in order to prevent large clearing sizes. At the landscape level, the management agent observes limits of sustainable harvest, i.e., ensuring that the landscape-scale harvest level remains at or below the level of long-term timber increment. A detailed description of ABE can be found in Rammer and Seidl (2015). Comprehensive model documentation for all iLand components is available at http://iLand.boku.ac.at, where also the model code and executable can be obtained under an open source license.

iLand was thoroughly evaluated for different forest types in Central Europe and the Western US. For the forests of the Northern Front Range of the Alps, simulated productivity, natural vegetation dynamics, and disturbance patterns were successfully compared to independent empirical data in previous studies (Seidl and Rammer, 2017; Thom et al., 2017a). The management response of the model was evaluated in detail by Seidl et al. (2017b). For the Weissenbachtal study landscape, Albrich et al. (2018) confirmed that iLand is able to reproduce the expected vegetation zoning and productivity patterns across the landscape. Furthermore, the ability of ABE to simulate realistic management trajectories at Weissenbachtal were successfully evaluated (Albrich et al., 2018).

2.3. Model initialization

The current vegetation structure and composition of the landscape was used as the starting point for all analyses. Aggregated information on vegetation (e.g., stem density, growing stock, tree species composition, stand age) representing the year 2013 was available from management plans of the AFF for 1678 stands (mean stand size 3.4 ha, Fig. 1). In addition, we used data from a plot-based forest inventory of the AFF to amend stand-level information with individual-tree level data (e.g., diameter at breast height [dbh], tree height). The positions of individual trees within a stand as well as the horizontal structure of the canopy (e.g., gaps) were determined from airborne laser scanning (LiDAR) data (horizontal resolution 1 m). Areas not suitable for tree growth such as rocky outcrops where identified based on a joint analysis of Lidar data and aerial photos, and masked in the simulation. In total, more than 1.7 10^6 trees >4 m height were initialized on the landscape. The average stand age was 86 ± 52 years (mean ± standard deviation), with a mean growing stock of 150 ± 156 m^3 ha^{-1}.

A spatially explicit site classification was available for the landscape based on the site types described in Weinfurter (2004). Quantitative soil characteristics for site types were derived from a database of forest soil characteristics based on the Austrian Forest Soil Survey AFSS (Seidl et al., 2009). Within site types and elevation bands the spatial variation recorded by AFSS sample plots was preserved by randomly assigning plot-level data to 100 m grid cells in the simulation. Soils are predominately shallow (mean ± standard deviation of effective soil depth 200 ± 74 mm), with a sand content of on average 31.2 ± 18.9% and an annual plant-available nitrogen of 49.5 ± 3.5 kg ha^{-1} yr^{-1}. Also initial litter and soil carbon pools were derived from AFSS data.

2.4. Climate scenarios

Simulations were run over 200 years and were driven by a total of seven different climate scenarios. The climate of the years 1950–2010 was used as baseline climate, representing the conditions of the recent past. Years were resampled randomly with replacement to derive a stationary 200 year climate baseline for simulation. Six climate scenarios represent potential future climate conditions. Scenarios were derived from three different combinations of global circulation models (GCM) and regional climate models (RCM), and were available at 25 km horizontal resolution. They were bias-corrected and statistically downscaled to 100 m horizontal resolution using a two-stage approach: First, we used a high resolution climate dataset of the Austrian Central Institution for Meteorology and Geodynamics (ZAMG, 2015) to interpolate climate information to a 1 km horizontal resolution. Subsequently, we used daily lapse rates to further downscale the information to the 100 m grid cells used for simulation. The RCM-GCM model combinations were CNRM-RM4.5 driven by ARPEGE (Radu et al., 2008), as well as MPI-REMO (Jacob, 2001) and ICTP-RegCM3, both driven by ECHAM5 (Pal et al., 2007). For all runs A1B forcing was assumed (IPCC, 2000), with previous analyses showing that the resulting temperature and precipitation changes lie between those expected from RCP4.5 and RCP6.0 for our study area (Thom et al., 2017b). Relative to baseline climate, temperature increases were +3.2 °C to +3.3 °C for 2080–2099, with annual precipitation sums changing by between −84 mm and +160 mm in the different scenarios (see Supplementary Figs. S1 and S2 for details). Beyond the year 2099, climate was assumed to remain stable at the 2080–2099 values, with years resampled randomly with replacement.

For all three climate model scenarios two alternative scenarios of future peak wind speed were simulated, resulting in a total of six scenarios of future climate. Deriving the future trajectories of peak wind speed from climate models at the scale of forest landscapes remains highly uncertain (Feser et al., 2015; Matulla et al., 2008). We thus developed two wind speed scenarios based on past wind data for our study area, corresponding to stable and increased peak wind speeds. In the former we assumed a continuation of historic extreme wind climate, and used the storm “Kyrill” (year 2007) to represent the 90th percentile of the wind speed distribution. For the latter we assumed a 10% increase in peak wind speeds, based on recent analyses suggesting potential future wind speed changes for Central Europe (Rockel and Woth, 2007). Wind directions were similar in all scenarios and were assumed to remain the same as in the past. For all scenarios wind events were drawn from the respective distributions and their effects simulated dynamically in the iLand wind module (Seidl et al., 2014a). Throughout the remainder of the manuscript, the six scenarios of potential future climate trajectories are jointly referred to as future climate.

2.5. Risk management strategies

The management baseline for our analyses forms a strategy strongly focused on Norway spruce, loosely corresponding to the historical management applied in the area. In this strategy (PA), spruce is planted after clear-cut harvesting, one to two thinnings are performed (depending on site quality) after an early tending intervention, and stands are harvested after 120–140 years (with longer rotation periods at higher elevations). Other tree species such as beech regenerate naturally on the landscape and are thus present in stand development, but are not actively promoted by management. While Norway spruce is a highly productive species, it is also assumed to be at high risk from natural disturbances, particularly under climate change (Neuner et al., 2015). The three alternative risk management strategies investigated (RM1-3) thus focus on reducing the share of Norway spruce, while at the same time decreasing the rotation period, as older forests are particularly vulnerable to disturbances from wind and the European spruce bark beetle (Netherer and Nopp-Mayr, 2005; Pasztor et al., 2014). RM1 aims at limiting the share of Norway spruce to between 30% and 70% of the basal area per stand (depending on site type and elevation), and introduces European larch (*Larix decidua*, L.) as admixed species, which is less wind-prone than spruce. This strategy corresponds to the approach currently implemented by

the AFF at Weissenbachtal (see also Albrich et al., 2018). RM2 goes one step further, aiming for mixed stands of three to four tree species per stand, and promoting a range of mixtures of spruce, beech, larch, fir and Scots pine (*Pinus sylvestris* L.), depending on site type and elevation. Target species compositions in this strategy were based on the management recommendations by the local Forest Service (Jasser and Diwold, 2014). Finally, strategy RM3 assumed that the forest composition emerging naturally under the conditions expected for the future would be of low vulnerability to disturbance. We thus selected the target tree species of RM3 to correspond to the simulated potential natural vegetation composition under climate change. The main target species of RM3 is beech; other admixed species are spruce, fir, pine and oak species (*Quercus petrea* Matt. and *Quercus robur* L.). In both RM2 and RM3, rotation ages were reduced to 120 also for high elevation stands in order to reduce risk (see Table 1). Overall, the strategies RM1-3 represent a gradient of progressively increasing intensity of risk management. All management strategies were adopted to the varying site conditions on the landscape and implemented at the stand level. As the Austrian Forest Act requires forest owners to salvage freshly killed trees in an effort to prevent insect outbreaks (Anonymous, 2017), we assumed a 90% detection probability of managers for blowdown and beetle kill, and removed detected trees in the current year in all management strategies.

2.6. Analyses

First, we analyzed the effect of future climate on natural disturbances from wind and European spruce bark beetle (henceforth in short referred to as bark beetle). Testing our first hypothesis we compared the cumulative timber volume disturbed under past climate over the 200 year simulation period (averaged to m^3 ha^{-1} yr^{-1}) against simulations under future climate using permutation tests. Furthermore, we investigated if and how the different risk management strategies influenced the simulated disturbance levels. In all subsequent steps, we focused our analyses on the simulations under future climate. To address our second hypothesis we explored the simulated level of disturbances spatially by visualizing them with maps of the study landscape. Subsequently, we investigated the inequality in the contribution of each stand to the overall disturbance level by generating Lorenz curves (Gastwirth, 1972), i.e., plotting the cumulative density distribution of stands over their contribution to the overall disturbance level, with stands ordered from low to high disturbance. The same analysis of spatial contribution was conducted for regular harvest, i.e. the target variable of timber-oriented management. Inequalities were assessed numerically by calculating Gini coefficients (Gastwirth, 1972), and differences between management strategies tested using Tukey's HSD test.

For testing hypothesis three we calculated the efficiency of risk management by deriving the maximum risk reduction obtained from the implementation of strategies RM1-3 (i.e., the percent reduction of disturbance under the best performing RM relative to PA). This analysis was conducted at the stand level, allowing us to categorize every stand in a risk matrix based on its leverage (i.e., its contribution to the overall risk at the landscape level) and the management control over risk (i.e., the maximum obtainable risk reduction from implementing different risk management strategies) (see also Cottin and Döhler, 2009; Seidl, 2014). We divided the risk matrix into four quadrants, using the average leverage of all stands and a 50% disturbance reduction relative to PA to discriminate the four quadrants. Subsequently, we used multinomial logistic regression to explore which aspects of landscape heterogeneity determine a stands position within the risk matrix. The explanatory variables considered were site variables (i.e., elevation, site quality) and initial stand condition (i.e., initial stand age and initial share of Norway spruce). To facilitate the interpretation of the results of the multinomial logistic regression model all explanatory variables were converted to z-scores.

For all stand-level analyses we controlled for the size differences of individual stands by exclusively using per unit area values. To address the stochasticity in the simulation of natural disturbances, 20 replicates of each combination of climate scenario (7) and management strategy (4) were simulated, resulting in a total of 560 simulations over a 200 year period. All analyses of simulation outputs were conducted with the R Project for Statistical Computing (R Development Core Team, 2017), specifically using the packages dplyr (Wickham et al., 2017), raster (Hijmans, 2016), perm (Fay and Shaw, 2010), and mlogit (Croissant, 2013).

Table 1
The baseline management strategy (PA) and the three risk management strategies (RM1-3) studied. Values for rotation period and tree species composition are area-weighted means over all stands, with the range of rotation periods indicated in parenthesis. All thinnings were selective thinnings from above. Simulated tree species composition is the average over the 200 year simulation period and the 20 simulated replications (future climate), with all strategies starting from the same initial conditions (i.e., current species composition). Piab: Norway spruce; Abal: silver fir, Fasy: European beech, Pisy: Scots pine, Lade: European larch, Qusp: oak species.

Management strategy	Target rotation period (years)	Thinning regime	Simulated tree species composition (% of basal area)	
PA	131 (120–140)	1–2 thinnings age bracket: 40–60 yrs removal: 30%	Piab: 52.7% Fasy: 19.6% Lade: 17.1%	Abal: 0.5% Pisy: 1.6% Qusp: 0.9% Other: 7.6%
RM1	131 (120–140)	1–2 thinnings age bracket: 40–60 yrs removal: 30%	Piab: 40.8% Fasy: 30.6% Lade: 18.4%	Abal: 0.6% Pisy: 1.9% Qusp: 0.9% Other: 6.8%
RM2	120 (120–120)	2 thinnings age bracket: 30–60 yrs removal: 30%	Piab: 22.4% Fasy: 40.2% Lade: 19.6%	Abal: 6.9% Pisy: 3.0% Qusp: 1.0% Other: 6.9%
RM3	120 (120–120)	2 thinnings age bracket: 30–60 yrs removal: 30%	Piab: 20.3% Fasy: 42.9% Lade: 14.6%	Abal: 6.0% Pisy: 2.8% Qusp: 7.6% Other: 5.8%

3. Results

3.1. Changing disturbances and the potential effect of risk management

Climate change substantially increased disturbance activity on the landscape. Under the PA management strategy, the average amount of timber affected by wind and bark beetles over the 200 year simulation period was 1.90 m^3 ha^{-1} yr^{-1} under past climate, increasing to 2.65 m^3 ha^{-1} yr^{-1} (+39.5%) under future climate. The ratio between disturbed timber and regular harvest was 0.285 and 0.368 under past and future climate, respectively. While there was considerable variation in the projected future level of disturbance activity (Fig. 2), disturbances under future climate increased significantly compared to simulations under past climate ($p < 0.001$). Under past climate, bark beetles accounted for approximately half of the total amount of timber disturbed (53.2%) under PA management, with the other half being attributed to wind disturbance. Under future climate the importance of bark beetles increased considerably, with 66.1% of all disturbances being caused by beetles.

The three risk management strategies investigated all considerably reduced disturbances on the landscape (Fig. 2). Under past climate, disturbance levels were 23.6% (RM1), 46.0% (RM2), and 48.6% (RM3) lower compared to the spruce-oriented baseline management strategy (PA). In response to future climate, disturbances increased also in the risk management strategies, but these climate effects were comparatively small, particularly for the strategies RM2 and RM3 (RM1: +0.53 m^3 ha^{-1} yr^{-1} $p < 0.001$, RM2: +0.28 m^3 ha^{-1} yr^{-1} $p < 0.001$, RM3: +0.17 m^3 ha^{-1} yr^{-1} $p = 0.002$). For the latter two management strategies, disturbance levels under climate change were significantly lower than disturbance levels under PA management and past climate. Overall, risk management reduced the ratio between disturbed timber and regular harvest to 0.313 (RM1), 0.212 (RM2), and 0.195 (RM3) under future climate. Risk management strategies specifically decreased bark beetle disturbances, with their share on the total amount of timber disturbed under future climate decreasing to 43.5% under RM3.

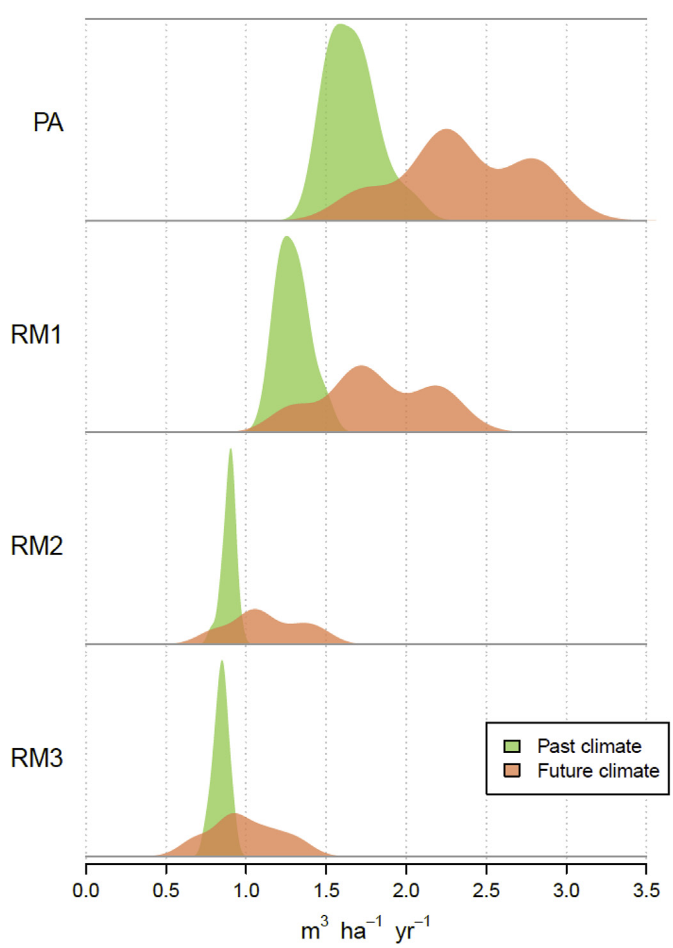

Fig. 2. Disturbance risk under past and future climate, expressed as the amount of timber disturbed by wind and European spruce bark beetle per hectare and year at the landscape scale over a 200 year simulation period. Future climate comprises six different climate scenarios for 2014–2213, while past climate represents the conditions of 1950–2010. Distributions indicate the probability density over the 20 replicated simulations and all climate scenarios, with management strategies in rows (see Table 1 for details).

3.2. Asymmetric contribution to risk in space

The contribution of individual stands to the overall disturbance risk was asymmetric (Fig. 3). The top 10% of the stands contributed 18.7% of the disturbed timber volume under PA management, and 50% of the disturbed volume accrued in 36.0% of the stands. Risk management further increased the spatial asymmetry of disturbance (Fig. 4). While for some stands the impact of disturbances remained high despite the risk management measures implemented under RM1-3, the disturbance effect was considerably reduced for others. Consequently, the relative contribution of high risk stands and thus the spatial asymmetry of risk increased under the RM strategies. Under RM3, the top 10% of the stands contributed 25.6% of the disturbed timber volume, and 50% of the disturbed volume accrued in 25.2% of the stands. This increasing asymmetry is also reflected by an increasing Gini coefficient along the gradient of intensifying risk management from RM1 to RM3 (Table 2). In contrast, the relative contribution of individual stands to regular harvest was considerably less spatially asymmetric, and alternative management strategies had only a marginal influence on this asymmetry.

3.3. Identifying priorities for risk management

The previous analyses highlighted that there is considerable spatial asymmetry (i) in the leverage of an individual stand on overall risk, and (ii) in the control over risk exerted by the three risk management strategies (i.e., the degree to which risk can be reduced). Combining these two dimensions into a risk matrix (see also Cottin and Döhler, 2009; Seidl, 2014) we grouped stands into four categories of risk response: First, stands which have a high leverage on risk and for which risk can effectively be controlled by management are suggested as priority areas for risk mitigation (Fig. 5) (24.4% of all stands). Second, stands for which risk can be controlled effectively, yet which are less influential with regard to overall risk (42.0%), can still be considered for risk management, if ample resources are available. Third, stands which neither make a strong contribution to landscape-scale risk nor can be substantially influenced by management could be ignored by management focusing on risk mitigation (16.9%). Finally, stands which have substantial leverage on risk, yet for which risks cannot be effectively controlled by management (16.7%) indicate areas for which the currently available risk management strategies are not effective. More research is needed in order to develop strategies for efficiently addressing risks in these stands. Analyzing how factors of landscape heterogeneity influence these groups of risk response by means of multinomial logistic regression showed that priority

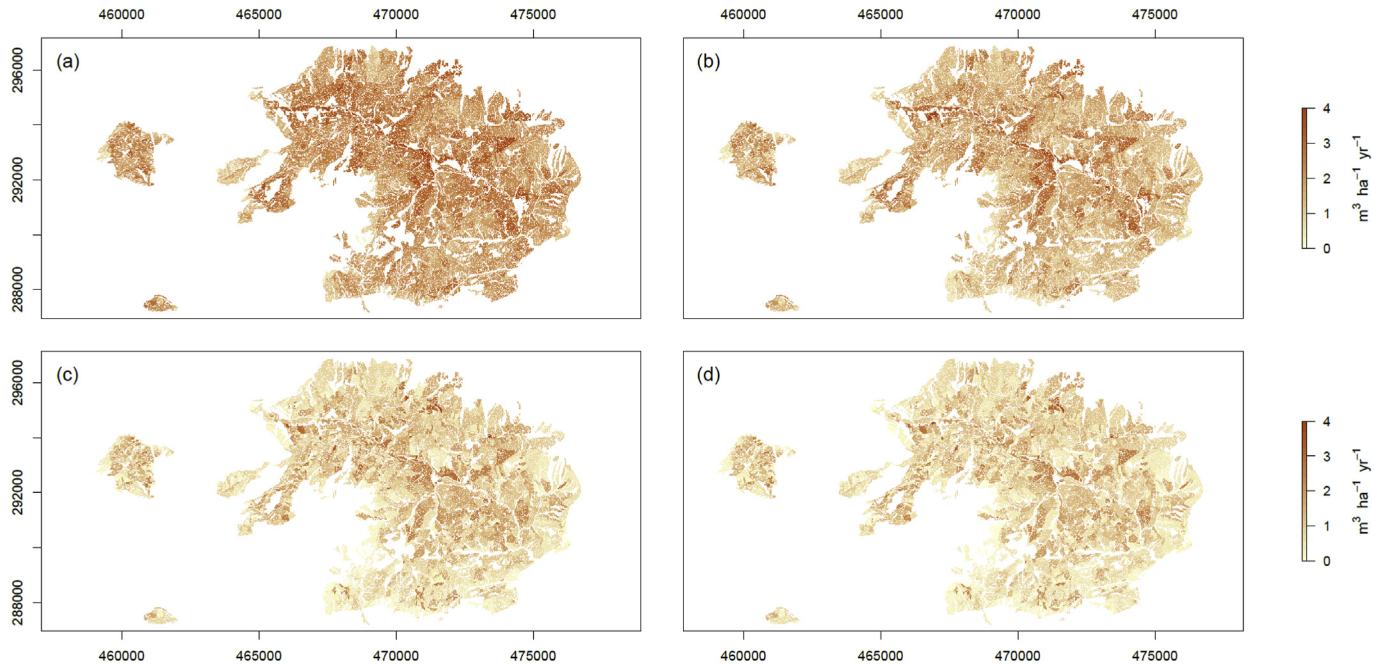

Fig. 3. Disturbance risk under future climate, expressed as the average amount of timber affected by wind and European spruce bark beetle per hectare and year over a 200 year simulation period. (a) Norway-spruce focused forest management (PA). (b)–(d) risk management strategies RM1-RM3, focusing on increasing the level of mixed and deciduous forests, and increasing the management intensity (see Table 1 for details). Shown is the stand-level mean over six different climate scenarios and 20 replicated simulations per scenario.

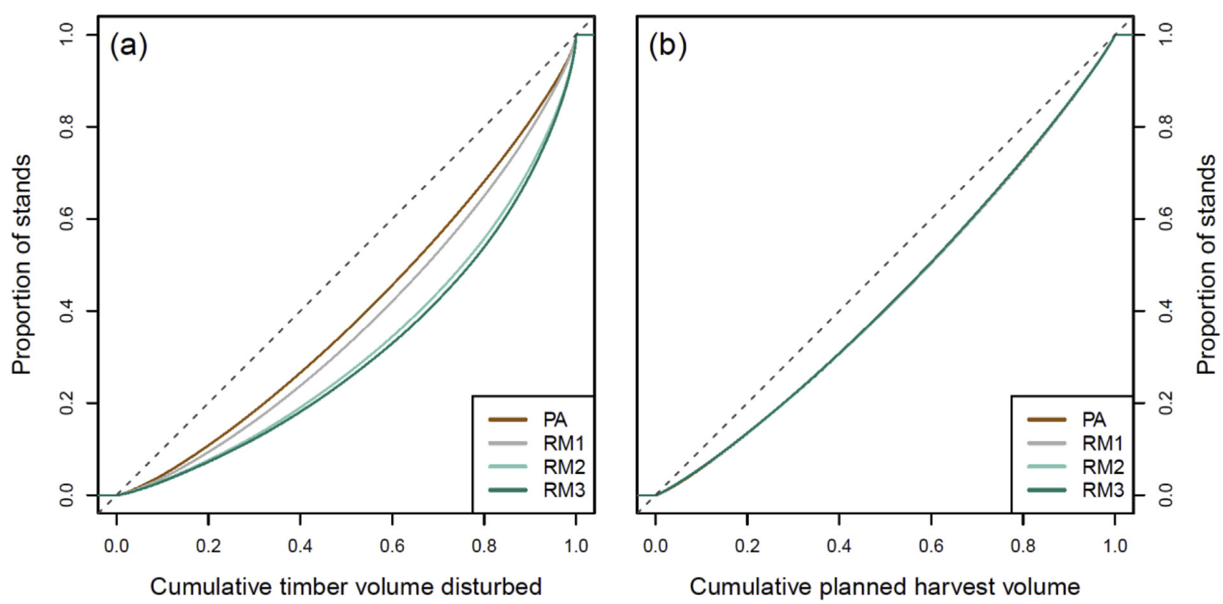

Fig. 4. Lorenz curves showing the cumulative contribution of individual stands to (a) the total timber volume disturbed, and (b) the total amount of regular timber harvest in different management strategies over a 200 year simulation period. PA = Norway-spruce focused forest management, RM1-3: risk management strategies. The 20 replicated simulations were averaged for the 1678 stands, and values were standardized to per unit area in order to control for the effect of different stand sizes. The grey dashed line indicates a hypothetical case in which every hectare on the landscape contributes equally to risk and regular harvest. Please note that in panel (b) the four strategies are almost identical, which is why only a single line is visible.

areas for risk management are situated predominately in the low-lying parts of the landscape and on better sites (Table S1). Also in stands that are currently old risk response should be prioritized. Stands that have a high share of Norway spruce currently are contributing disproportionally to the timber volume disturbed, but are at high risk of being disturbed regardless of management strategy ("Research" group in Fig. 5).

4. Discussion and conclusions

Here we show that climate change increases the disturbance risk in managed forests of Central Europe, and that targeted risk management substituting mixed forests for Norway spruce-dominated systems can substantially reduce these risks. Our findings of increasing disturbance activity under future climate (+39.5%

Table 2
Asymmetry of stand contributions to disturbance and regular harvest, expressed as their Gini coefficient. Values are means (standard deviation in parenthesis) over the entire range of future climate scenarios and replicates (n = 120 for each management strategy). Letters indicate significant differences between management strategies (i.e., within columns), determined by means of Tukey's HSD test at $\alpha = 0.05$.

Management strategy	Disturbance	Regular harvest
PA	0.293^{a} (0.023)	0.194^{a} (0.018)
RM1	0.322^{b} (0.023)	0.192^{a} (0.015)
RM2	0.440^{c} (0.024)	0.174^{b} (0.016)
RM3	0.466^{d} (0.026)	0.174^{b} (0.016)

under PA management) is well in line with global assessments of disturbance change, reporting an expected disturbance increase under climate change of on average +38.0% in temperate forest ecosystems (Seidl et al., 2017a). A recent study focusing on an unmanaged landscape of the same forest types in the Alps reports a somewhat lower disturbance increase of +27.7% over 200 years, which is likely the result of autonomous adaptation processes in unmanaged systems (Thom et al., 2017c). While other assessments find a higher climate sensitivity of disturbances in Europe (Jönsson et al., 2009; Seidl and Rammer, 2017) it is important to note that our simulations assume effective beetle management via salvage harvesting, and account for negative feedbacks on disturbance via stand structure (e.g., a forest disturbed by wind takes several decades before it again becomes susceptible to wind disturbance; see also Temperli et al., 2013). Our analyses are also in congruence with previous assessments regarding the projected increase in importance of disturbances from bark beetles in Central European forests (Netherer and Schopf, 2010; Seidl and Rammer, 2017). Already over the past decades, disturbances from bark beetles increased more strongly than those from wind or wildfire in Europe (Seidl et al., 2014b). Future climate is likely to foster beetle development while weakening tree defenses against beetles (Jönsson et al., 2009; Netherer et al., 2015). The fact that reducing the prevalence of Norway spruce – the host tree of the European spruce bark beetle – was found to be an effective measure of disturbance risk management is thus largely an effect of the growing importance of bark beetles in the disturbance regime of Central Europe.

Spatial risk management of spreading biotic disturbances such as bark beetles also entails the consideration of host aggregation and landscape connectivity (Cairns et al., 2008; Seidl et al., 2016c). While the risk management strategies investigated here focused largely on reducing the highly risk-prone Norway spruce and increasing mixed forests (Neuner et al., 2015), future work could further improve risk management by deliberately modifying spatial configuration and composition of the landscape in order to reduce contagion (Seidl et al., 2016b). While we here did not address this aspect, it has to be noted that our analysis of disturbance risk does explicitly consider neighborhood relationships. For example, if a stand on deep soils (which allow deep rooting and ample water supply, and thus can be expected to have high stability against wind and optimal defenses against bark beetles) is situated next to a disturbance-prone, wind-exposed ridge with shallow soils, the former is still subject to increased beetle pressure via bark beetles spreading from the latter in our spatially explicit simulations. In terms of the spatial distribution of disturbances across forest landscapes our analysis thus goes considerably beyond stand- or site-based assessments of disturbance predisposition and risk, which usually do not consider the effect of neighboring stands (Netherer and Nopp-Mayr, 2005; Pasztor et al., 2014).

Spatial asymmetries on the landscape were considerably stronger for disturbance risk than for regular harvest. This finding suggests that while harnessing spatial heterogeneity for risk management, potential detrimental effects on regular harvest are small. This is a novel insight of high relevance for risk management, illustrating the potential of landscape approaches particularly in the forests of Central Europe, where the stand remains the primary focal unit of management. Future work on forest management planning in the area should make increasing use of concepts and

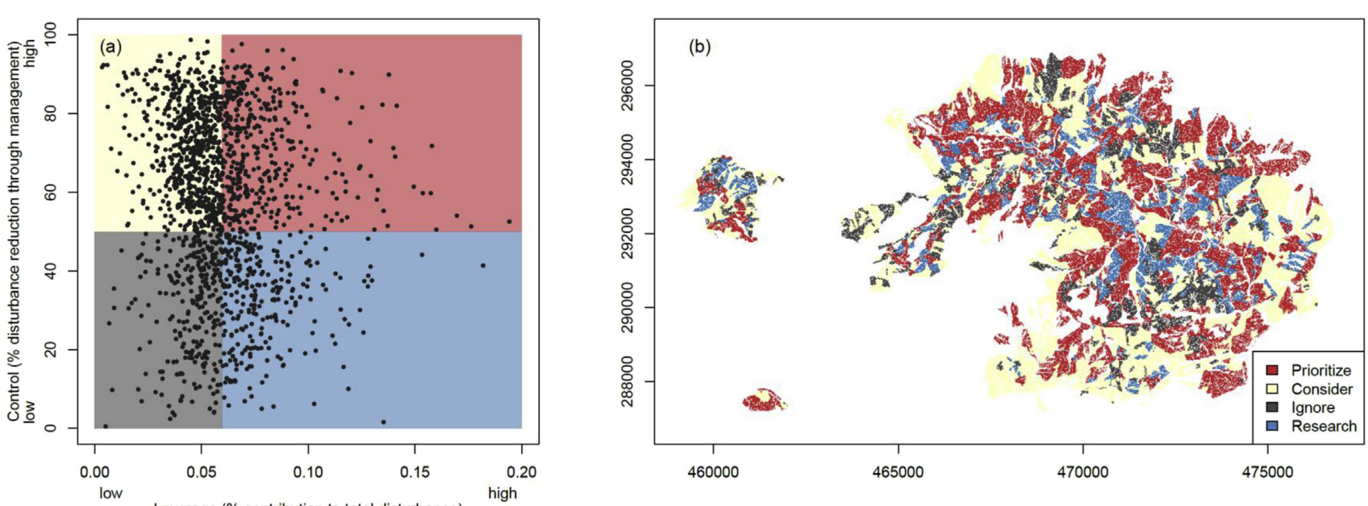

Fig. 5. (a) Influence matrix categorizing the 1678 stands according to their leverage on disturbance risk (i.e., a stand's contribution to the total landscape-scale disturbance level) and the level of control exerted by the three risk management strategies investigated (i.e., the maximum level of disturbance reduction relative to the baseline management strategy PA). The influence matrix was divided into four quadrants, using the average contribution of all stands (x-axis) and a 50% disturbance reduction relative to PA (y-axis) for discrimination. The four deduced groups of risk response were: Prioritize (red): stands have a high leverage on overall risk, and risk can be reduced effectively; Consider: also here risk can be reduced with available risk management strategies, but their leverage on overall risk is low; Ignore: low leverage on overall risk in combination with low level of risk control suggest that risk mitigating measures are not advisable; Research: stands with high leverage on overall risk, for which currently available risk management strategies are not able to deliver a substantial risk reduction, hence requiring more research and the exploration of alternative risk management options. Please note that stand-level values were standardized to per unit area in order to control for the effect of different stand sizes. For the sake of clarity, four outliers along the x-axis are not shown. (b) Spatial distribution of the four risk response categories across the Weissenbachtal landscape. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

ideas of landscape ecology (Turner et al., 2013), and explore space as a new frontier of ecosystem management (DeAngelis and Yurek, 2017).

Addressing changing disturbance regimes is one of the major challenges for current ecosystem management. A recent questionnaire study among managers in Austria, for instance, identified disturbance change as the key issue of concern for practitioners (Seidl et al., 2016a). Addressing risks from disturbances is particularly challenging, as natural disturbances simultaneously affect the objectives of ecosystem management positively and negatively (Thom and Seidl, 2016). We here present an approach to address this issue via a spatially stratified risk response, derived from a simulation-based risk matrix. Following the suggestion that risk reduction is most powerful where both the probability of occurrence *and* the level of control are high (Seidl, 2014) we here demonstrate how spatial heterogeneity can be used to identify priority areas for disturbance risk reduction. As resources for risk management are usually limited, such a spatial prioritization can help to increase the overall efficiency of risk management measures, e.g., in economic terms. However, our categorization also identifies areas of the landscape where embracing natural disturbances (rather than aiming to mitigate them) is likely the best course of action, because both the leverage and control of disturbance risk is low. For these areas, accounting for 16.9% of the stands in our study landscape, management could focus on the positive effects of natural disturbances on biodiversity and adaptive capacity (Beudert et al., 2015; Thom et al., 2017b; Wermelinger et al., 2017), rather than applying a spatially uniform disturbance prevention approach across the entire landscape. Our analysis thus illustrates how spatial heterogeneity can be harnessed to address natural disturbances in ecosystem management.

Risk management in forest ecosystems needs to consider the multiple ecosystem services provided to society. Beyond the provisioning of biomass and the conservation of biological diversity, the managed forests of Central Europe provide a wide variety of other ecosystem services. While we here focused on disturbance risks on a single ecosystem service, timber production, other services such as the protection against gravitational natural hazard, recreational use of forests, soil conservation, and carbon sequestration are important for our study landscape (Albrich et al., 2018; Mayer et al., 2017). Consequently, future work should extend spatial risk management approaches to include a broader range of ecosystem services, and explicitly consider their synergies and trade-offs. Considerations of spatial heterogeneity could not only help to address risks of changing climate and disturbance regimes, but also to optimize trade-offs between the provisioning of different ecosystem services (Härtl et al., 2015; Lafond et al., 2017).

Important uncertainties remain with regard to the future trajectories of forest ecosystems. In the context of our current analysis uncertainties regarding the future development of peak wind speeds can be exemplarily highlighted. Wind is currently the most important abiotic disturbance agent in Central Europe, and frequently triggers bark beetle outbreaks (Stadelmann et al., 2014). Yet the future storm climate of Central Europe remains highly uncertain. More broadly, we here constrained our analysis to the two currently most important disturbance agents, ignoring potential threats from other agents such as invasive alien pest species (Pautasso et al., 2010; Santini et al., 2013). However, as climate and tree species composition change, other biotic disturbance agents – both native and alien – could increase in importance in the future (Ramsfield et al., 2016). Future efforts should thus explicitly consider a wider range of biotic disturbance agents and their interactions, in order to increase the robustness of risk management strategies.

As a wider consequence of such future uncertainties it is important to recognize that, while risk reduction is necessary to safeguard a continuous supply of renewable resources from forests, a command-and-control approach to forest disturbances is neither possible nor desirable (Holling and Meffe, 1996; Kulakowski et al., 2017). Reducing risks should thus be balanced with fostering resilience, i.e., the capacity of forests to recover from disturbances without significant changes in the processes governing the system. In particular, fostering resilience is an important response to changing disturbance regimes in areas which have a high leverage on overall risk, but for which the control over risk is low (i.e., the 16.7% of stands in the “Research” group in Fig. 5). Fostering resilience and strengthening the ability of the system to recover, e.g., by increasing the diversity on the landscape, is a powerful approach to address increasing future uncertainties in ecosystem management (Biggs et al., 2012; Seidl, 2014). We conclude that spatial heterogeneity at the landscape scale holds considerable potential for addressing the risks of changing climate and disturbance regimes in forest ecosystems. We advocate for landscape-scale management approaches harnessing spatial variability towards a robust provisioning of forest ecosystem services.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.12.014.

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